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THERMODYNAMIC AND ECONOMIC ANALYSES OF DESULFURIZATION WASTEWATER RECOVERY IN COAL-FIRED POWER PLANTS

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ABSTRACT

Zero emissions of waste gas and water from coal-fired power plants are one of the pathways for cleaner electricity production in China. It is expected to achieve low-cost zero discharge of flue gas desulfurization (FGD) wastewater by applying multi-effect distillation (MED) or multi-stage flash (MSF) technologies and matching different heat sources from the power plant. In the present work, four different integration schemes were proposed for FGD wastewater recovery by concentration and deep desalination. The thermo-economics of different schemes were analyzed in terms of gained output ratio (GOR) and energy cost. The results showed that the cost of auxiliary steam driven MED could be lowered by the integration of thermal vapor compression (TVC). The GOR of MED could be increased by 10%-100% while the energy cost was reduced by approximately 10%-50%. In contrast, the pump electricity consumption should be reduced when MED was driven by flue gas. Moreover, the MSF distillation had stronger adaptability to salt concentration than MED. The energy cost of flue gas driven MSF could be remarkably reduced by lowering the flash temperature difference.

Keywords: desulfurization wastewater, zero emissions, MED, MSF, energy cost, thermodynamic analysis

1. INTRODUCTION

With ever increasing stringent limit of pollution emissions from energy industry in China, flue gas desulfurization (FGD) system of coal-fired power plants, which accounts for nearly 60.2% of the total installed capacity [1], has become an indispensable choice. Limestone-gypsum wet scrubber technology is commonly applied in domestic coal-fired power plants. During the operation of desulfurization process, it is regularly necessary to discharge part of the wastewater to maintain the material balance of the system and prevent the enrichment of F^-, Cl^-, dust and other substances. Normally, the amount of desulfurization wastewater produced is 15 to 20 kg/(MW·h). Accordingly, the flow rate of desulfurization wastewater produced by 600 MW units was estimated around 10 m^3/h [2,3]. Although it is much lower than that in seawater desalination plants, the desulfurization wastewater is generally featured by high content of suspended solids, COD (chemical oxygen demand), fluoride and heavy metals such as As, Hg, Pb [4]. Besides, the salt content is high, including a large amount of SO_4^{2-}, SO_3^{2-}, Cl^- [5]. Therefore, the FGD wastewater cannot be directly discharged, and a separate treatment system is required to improve its water quality for reduced environmental concerns [6].

An extensive research has been carried out in seawater desalination using waste heat from coal-fired, nuclear and combined-cycle power plants [7-13]. At present, desulfurization wastewater is mainly treated by chemical precipitation method. However, it is difficult to reduce some water quality indexes to meet tha standard limits. Moreover, the existing waste water treatment technologies, such as flue evaporation [14], reverse osmosis and evaporation crystallization, have challenges such as no recovery and reuse of solid waste, incomplete water recovery, and high operation cost. In order to recover the wastewater effectively, evaporation methods can be applied to achieve crystallization desalination. The integrated processes of pretreatment, concentration, evaporation and crystallization could be implemented, in which the pretreatment technology is relatively mature [15].

Therefore, the present work focused on the matching of different heat sources of power plants with various concentrated desalination technologies. The main objective was to evaluate flue gas and auxiliary steam driven MED/MSF with/without thermal vapor compression (TVC), to search for more economically viable structure and working parameters based on thermodynamic modeling and economic analysis.

2. MATERIALS AND METHODOLOGY

2.1 System configuration

There are abundant sources of waste heat in coal-fired power plants. Particularly, auxiliary steam and boiler flue gas can be considered as heat sources for wastewater treatment from the perspectives of convenience and relatively low cost. Moreover, concentration and evaporation crystallization can be achieved by direct evaporation or single-stage cyclic flash evaporation, but the thermal efficiency is quite low. Therefore, the multi-effect distillation (MED) [16] and multi-stage flash evaporation (MSF) technologies are currently used in desalination in order to reduce the energy consumption [17].

As shown in Fig. 1, the following integration schemes have been investigated, including MED driven by auxiliary steam, MED-TVC driven by auxiliary steam, MED driven by flue gas, MED driven by flash steam and flue gas as heating source, and MSF driven by flue gas.

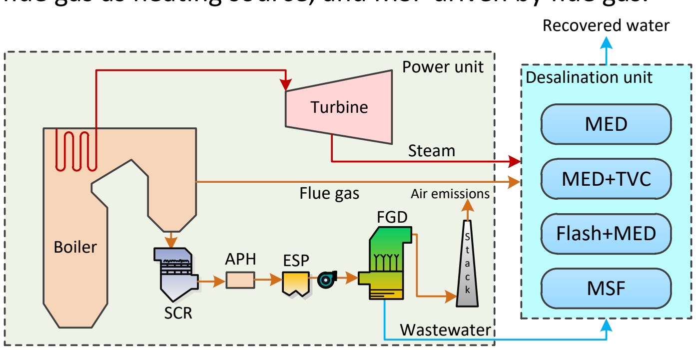

Fig. 1 Schematic of FGD wastewater recovery schemes

2.2 System models

2.2.1 MED process modeling

The counter-current series structure was implemented in the MED process. In particular, the auxiliary steam from power plants was used as heating medium in the first stage, in which complete desalination of the concentrated brine was achieved.

A thermodynamic model was established by taking one of the stages as an example, as shown in Fig. 2.

The conservation of mass can be written as:

$$m_{v[i-1]} + m_{v,f[i-1]} = m_{d[i-1]} \quad (1)$$

$$m_{w,in[i]} = m_{w,out[i]} + m_{v[i]} \quad (2)$$

$$m_{w,in[i]} \cdot S_{in[i]} = m_{w,out[i]} \cdot S_{out[i]} \quad (3)$$

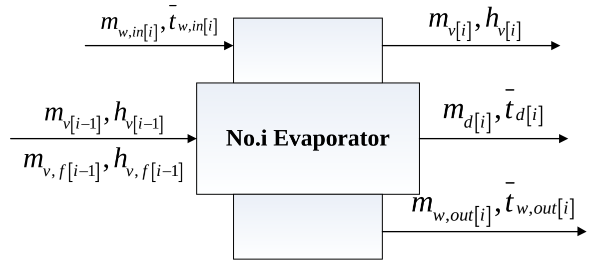

Fig. 2 *I*-stage evaporator model

The conservation of energy can be written as:

$$Q = m_{v[i-1]} \cdot h_{v[i-1]} + m_{v,f[i-1]} \cdot h_{v,f[i-1]} - m_{d[i]} \cdot \bar{t}_{d[i]} \quad (4)$$

$$Q = m_{v[i]} \cdot h_{v[i]} - m_{w,in[i]} \cdot \bar{t}_{w,in[i]} - m_{w,out[i]} \cdot \bar{t}_{w,out[i]} \quad (5)$$

where m is the mass flow rate (t/h), S is the salt concentration, h is the enthalpy (kJ/kg), t is the liquid working substance enthalpy (kJ/kg), w is the spray seawater, v is the secondary steam, d is the condensation water, f is the flash products, *in* is the inlet of the evaporator, and *out* denotes outlet.

The gained output ratio (GOR) can be calculated as:

$$\mathrm{GOR} = \sum m_{v[i]} / m_{v[0]} \quad (6)$$

2.2.2 Thermodynamic models of coal-fired power plant

The plant model was developed by GSE simulation software. Detail descriptions can be found in Refs. [2,3,6]. Moreover, MED/MSF calculation models were included into the plant model for overall performance evaluations.

3. RESULTS AND DISCUSSION

3.1 MED driven by auxiliary steam

In this scheme, the pretreated desulfurization wastewater, which mainly contained sodium chloride and sodium sulfate, was introduced into MED system, and the plant auxiliary steam was used as heating source until the salt-containing wastewater was enriched to near saturation. After that, crystallization and desalination were carried out.

A typical 600 MW unit was selected as the case. The auxiliary steam with parameters of 0.7 MPa/320 °C was used as heat source. The steam cost was estimated at 50 CNY/t. The initial temperature of the wastewater was 60 °C, and the initial concentration (s_0) was 5%.

It can be seen from Fig. 3 that the GOR increased linearly with the number of process stages. However, there was a limit in the effectiveness of MED due to saturation concentration before entering the first stage, that is, the salt concentration could not exceed 26% (Fig. 4), and otherwise crystallization could occur during other effective falling film evaporation processes.

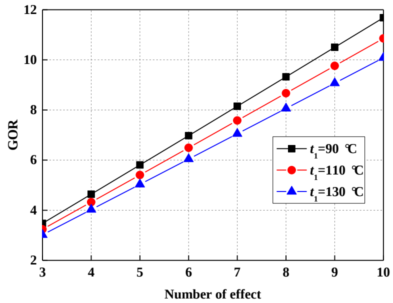

Fig. 3 GOR of MED in terms of number of stages under different temperatures of the first stage

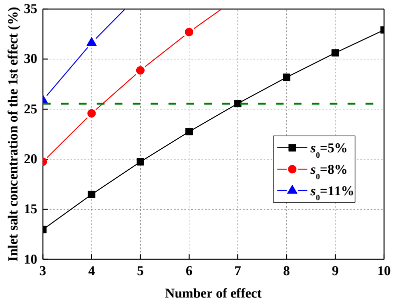

Fig. 4 MED first stage inlet salt concentration in terms of number of stage under different initial salt concentrations

3.2 MED+TVC driven by auxiliary steam

TVC could be incorporated with MED system to improve the GOR. The GOR and energy cost of using auxiliary steam as heat source to drive MED and TVC are shown in Fig. 5 and Fig. 6, respectively.

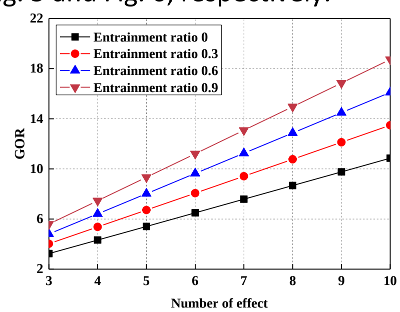

Fig. 5 GOR in terms of MED stage under different ejector entrainment ratios

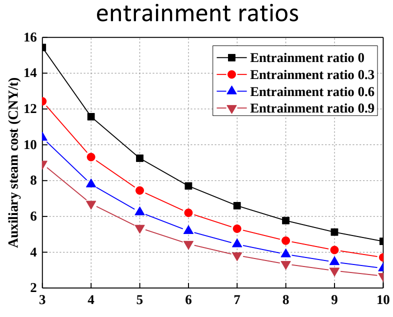

Fig. 6 The auxiliary steam cost in terms of MED stage under different ejector entrainment ratios

It can be found that the increase in the efficiency and the ejector ratio would lead to an enhancement in the GOR, thereby reducing the use cost of the plant steam. Take 6-stage MED as the example, the GOR increased by 72.3% (from 6.5 to 11.2), and as a result, the energy cost decreased by approximately 58% (from 7.7 CNY/t to 4.5 CNY/t). The cost of auxiliary steam driven MED could be lowered by the integration of thermal vapor compression (TVC). Overall, the GOR of MED could be increased by 10%-100% while the energy cost was reduced by approximately 10%-50%.

3.3 MED driven by flue gas

The flue gas from boilers could be used as heat source for MED by arranging the evaporating heat transfer surfaces in the flue, or extracting part of the flue gas into an external heater of the MED system. Since the energy cost of the flue gas was almost negligible, the main cost contributor was considered to be electricity consumption.

The costs associated with boost pump work were obtained and compared as shown in Fig. 7. It can be found that the pump power consumption cost decreased with the flash temperature drop. Moreover, the direct evaporation of recirculation water consumed much lower pump cost than the flash system.

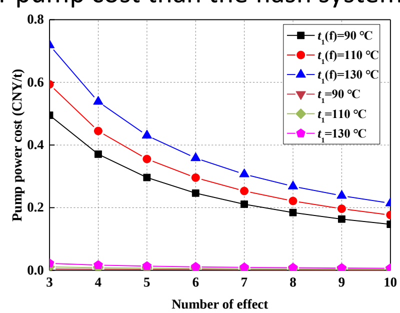

Fig. 7 The pump power cost in terms of MED stage under different first stage temperatures

3.4 MSF driven by flue gas

MSF can also be applied for wastewater desalination with flue gas as heat source. The concentrated brine is continuously crystallized during the flashing process, and the solid salt particles are separated at the final stage. The electricity cost of the pump power consumption is shown in Fig. 8 (electrical cost was calculated as 0.5 CNY/kW·h). The cost increased from 0.3 CNY/t to 1.15 CNY/t when the flash temperature increased from 120 °C to 200 °C.

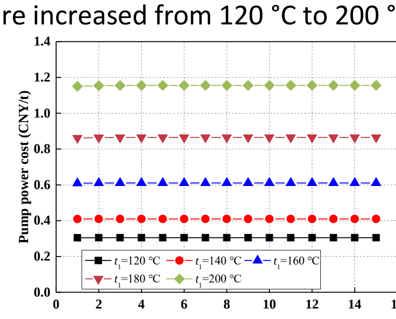

Fig. 8 The pump power cost in terms of number of stage

4. CONCLUSIONS

Flue gas and auxiliary steam available in coal-fired power plants can be invited as heat sources for MED/MSF treatment of FGD wastewater towards near zero-water-emissions. Therefore, different integration schemes were proposed and investigated in terms of gained output ratio and water production energy cost by thermodynamic modeling and economic analysis in the present work. The main conclusions are as follows:

(1) In the process of FGD wastewater treatment, energy cost of MED driven by plant auxiliary steam was generally above 10 CNY/t. The integration of TVC could reduce the energy cost by 10%-50%. The usage of flue gas could further reduce the cost by 90%.

(2) MED had relatively higher GOR, but it was not suitable for the initial salt concentration change of FGD wastewater and for treating high-salinity wastewater. In contrast, MSF distillation had better adaptability to salt concentration. Moreover, the cost of flue gas driven MSF could be effectively reduced by lowering the flash temperature difference.

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